ECE 371
Materials and Devices

08/22/19 - Lecture 1

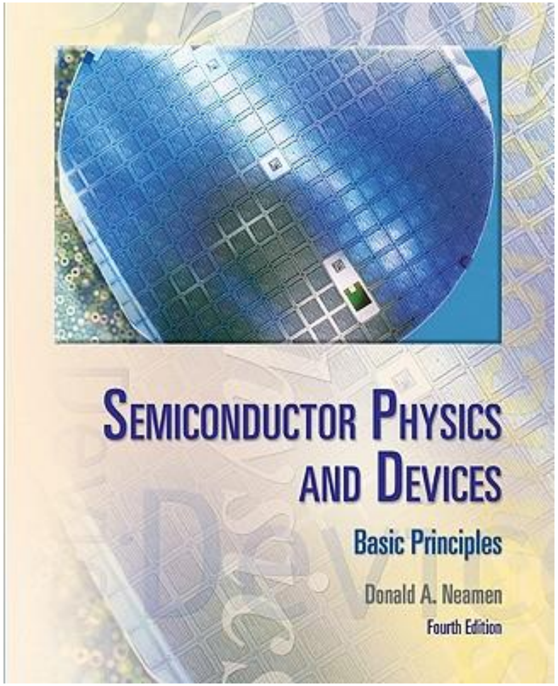
Introduction and The Crystal Structure of Solids

General Information

- **ECE 371 - MATERIALS AND DEVICES**
  - Semester: Fall 2019
  - Class Time: Tu-Th 11:00am-12:15pm
  - Class Location: Mitchell Hall 202
  - Class Website: UNM Learn (http://learn.unm.edu)
    - Syllabus, approximate course schedule and content, lecture slides, homework assignments and solutions, exam solutions, additional notes, videos, etc.
- **Instructor:**
  - Professor Daniel Feezell
  - Electrical & Computer Engineering Department
  - E-mail: dfeezell@unm.edu
  - Office Location: CHTM Room 112B
  - Office Hours: Thur 2 pm – 4 pm
- **Teaching Assistant:**
  - Mr. Hasan Ahmed
  - Electrical & Computer Engineering Department
  - E-mail: hasan@unm.edu
  - Office Location: TBD
  - Office Hours: Wed 10 am – 12 pm

Textbook

- **Required Text:**
  - "Semiconductor Physics and Devices: Basic Principles," D. A. Neamen, McGraw Hill, 4th edition (2012), ISBN: 978-0-07-352958-5.
    - The course will closely follow the text
    - The same text is used for ECE 471
    - ECE 371 covers chapters 1-5, 7, 8 (partial), and 10 (partial)



- **Reference Text:**
  - "Solid State Electronic Devices," B.G. Streetman and S. Banerjee, Prentice Hall, 5th edition (2000), ISBN: 0-13-025538-6

Grading

- **Grading:**
  - Homework (assigned approximately every other week) 30%
  - Midterm Exam 1 (Tuesday 9/24, 11:00am-12:15pm, covers ch. 1-2) 20%
  - Midterm Exam 2 (Thursday 10/31, 11:00am-12:15pm, covers ch. 3-5) 20%
  - Final Exam (Tuesday 12/10, 12:30pm-2:30pm, ch. 7,8,10) 30%
- **Homework Policy:**
  - Late homework assignments will typically not be accepted as I will post the solutions to the assignments right after you turn them in. Homework is due at the ***beginning of the class period*** on the due date. Homework should be neatly written, with each problem labeled and the pages stapled together. Show your work in a logical fashion in order to get maximum credit and *please box your final answers*! If the problem says "plot" you should use Excel, Matlab, or some other numerical tool, if the problem says draw or sketch, you can do it by hand.
- **Reading Assignments:**
  - Posted on the class schedule Excel spreadsheet on the web site. You should read through the material before each class session. The spreadsheet may be periodically updated depending on the class progress.

Homework #1 and Reading

- Homework #1 assigned on course web site and due on Tuesday September 3rd
- Reading for the first week: Neamen 1.1-1.7
- Check Excel spreadsheet on UNM Learn for HW and reading assignments

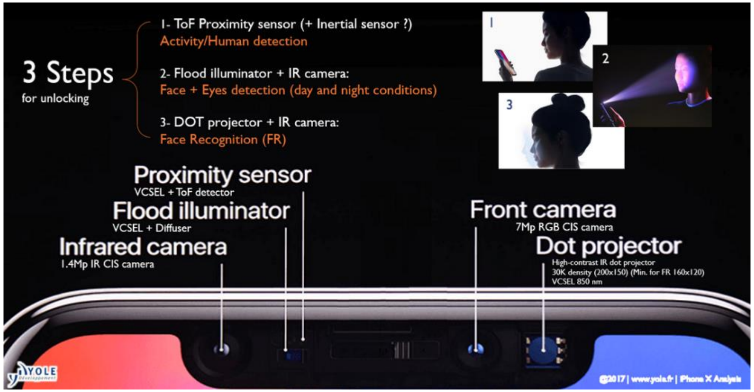
i>clickers

- This course will occasionally use i>clickers to create a more interactive learning environment. i>clickers can be purchased at a reduced price at the bookstore. For more information see:
- http://www1.iclicker.com/student-remote-iclicker-plus
- http://www.unm.edu/~oset/teachingwithclickers.html

Question

How many people in here have an iPhone in their pocket?

iPhone Contains Many Semiconductor Devices

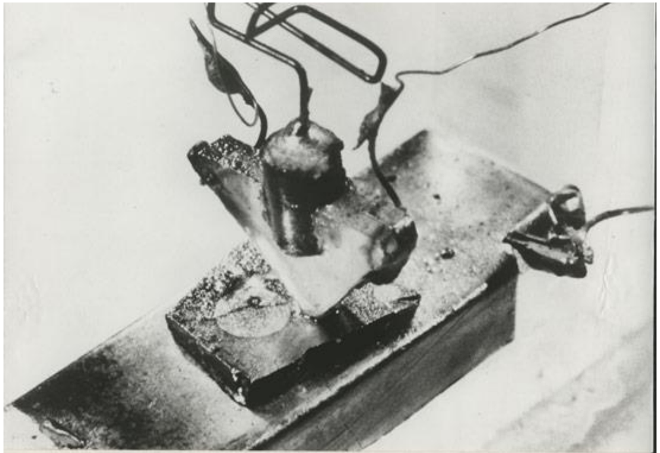


- **Transistors** – Pn junction
- **Integrated Circuits**
- **Emitters (VCSELs, LEDs, OLEDs)**

  Vertical cavity laser
- **Image and proximity sensors (detectors)**
- **Micro-mechanical systems** (MMS) "mems"

The Transistor

- Fundamental building block of modern electronic circuits
- Essentially a semiconductor-based switch



THE FIRST TRANSISTOR AS IT WAS PATENTED BY THREE NOBEL PRIZE-WINNING BELL LABORATORIES SCIENTISTS

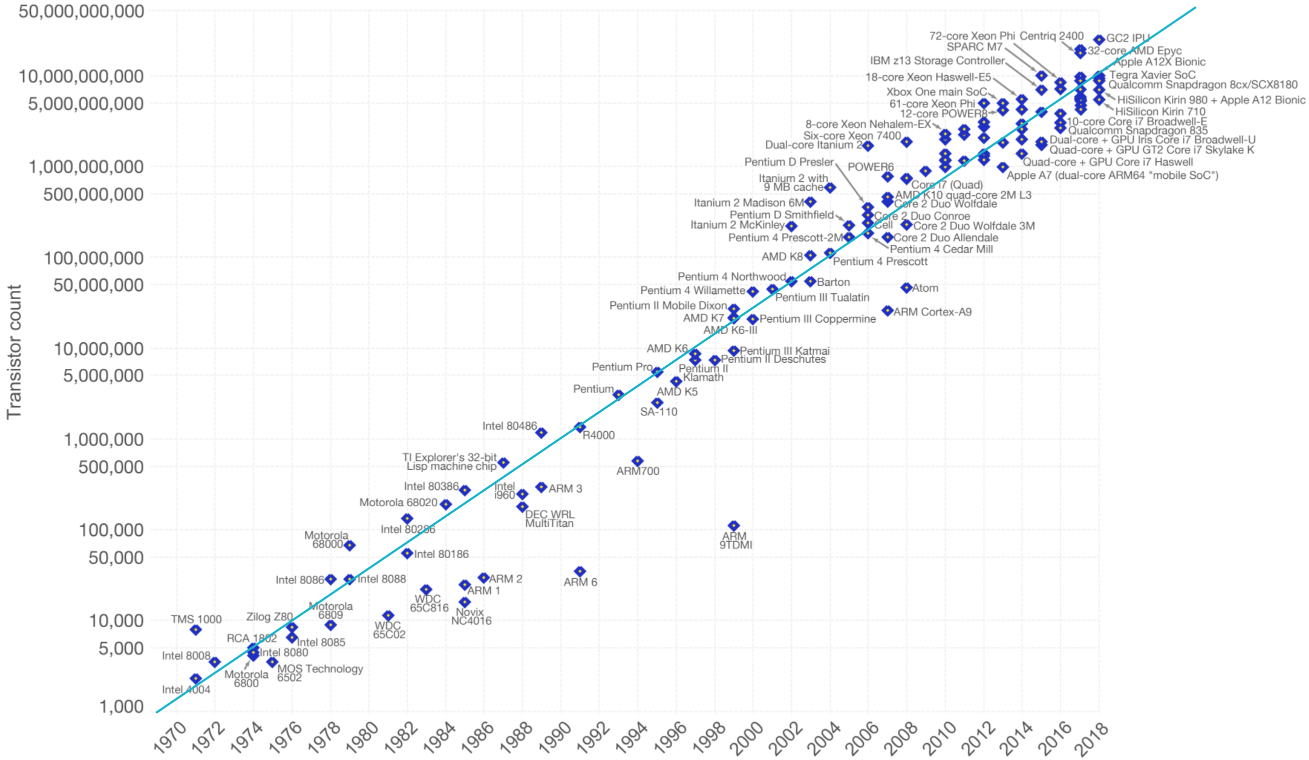
William Bradford Shockley | John Bardeen | Walter Houser Brattain

- 1st transistor size 3 cm
- Latest transistor size (node) is 5 nanometers (5×10^{-9} m)!
- Intel, IBM, TSMC, Samsung
  Taiwanese Semic. Manf.
- Primarily composed of silicon

Moore’s Law

Moore’s Law – The number of transistors on integrated circuit chips (1971-2018)

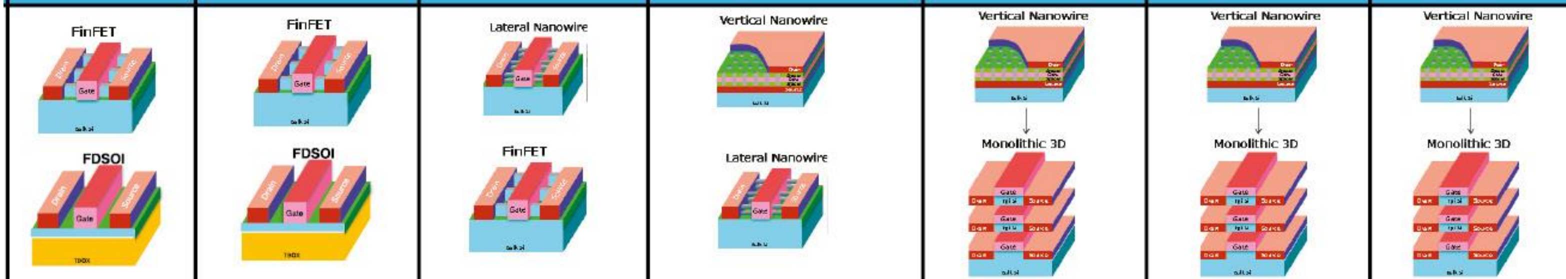
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Transistor Architectures (ITRS Roadmap)

2015	2017	2019	2021	2024	2027	2030
P70M56	P48M36	P42M24	P32M20	P24M12G1	P24M12G2	P24M12G3
"16/14"	"11/10"	"8/7"	"6/5"	"4/3"	"3/2.5"	"2/1.5"
finFET FDSOI	finFET FDSOI	finFET LGAA	finFET LGAA VGAA	VGAA M3D	VGAA M3D	VGAA M3D



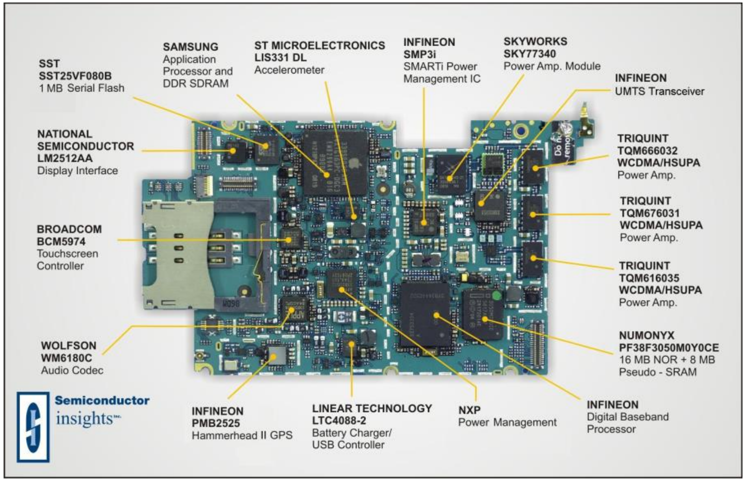
https://doi.org/10.1515/aot-2017-0039

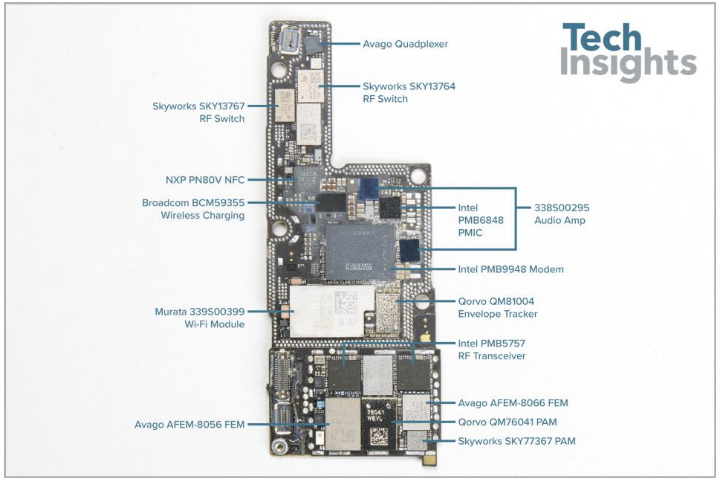
how does graphene come in?

- International Technology Roadmap for Semiconductors (ITRS)
- Size-scaling enables faster and lower power chips
- FinFETs – current technology fin-like structure
- Gate-all-around nanowire FETs – future technology, good electrostatics, challenges
- New channel materials for higher electron mobility (Ge and III-V materials)

Complicated Modern Electronics

Examples of integrated circuits:





[Apple A12X Bionic] (octa-core ARM64 "mobile SoC") contains 10 billion transistors in ~1.2 cm^2!

Course Objective

The primary objective of this course is to learn the fundamental physics of semiconductor materials and devices and to apply this knowledge to understand the operation of modern transistors

- **Crystal structures**
- **Quantum mechanics**
- **Electronic behavior of solids**
- **Electrons and holes (carriers)**
- **Energy bands**
- **Current/carrier transport**
- **Semiconductor PN junctions** ??
  basic diode
- **Metal oxide semiconductor (MOS) transistors**

Knowledge gained in this course also directly applies to light-emitting diodes, laser diodes, photodetectors, and solar cells

Classifying Materials

- **Insulator:** a material that does not conduct electric current (glass, paper, silicon dioxide). No free electrons.

- ***Semiconductor:*** a material that conducts electric current when certain impurities (dopants) are added (Si, Ge, GaAs). The conduction is controllable, making it suited for amplifying, switching, or converting signals. Some free electrons.

  phos. → 5 valence electrons
  1 extra to lose to surroundings

- **Conductor:** a material that does conduct electric current (copper, gold, aluminum). Many free electrons.

Semiconductor Materials

Group III	Group IV	Group V
5 **B** Boron 10.811 (2 3)	6 **C** Carbon 12.0107 (2 4)	7 **N** Nitrogen 14.0067 (2 5)
13 **Al** Aluminium 26.9815386 (2 8 3)	14 **Si** Silicon 28.0855 (2 8 4)	15 **P** Phosphorus 30.973762 (2 8 5)
31 **Ga** Gallium 69.723 (2 8 18 3)	32 **Ge** Germanium 72.63 (2 8 18 4)	33 **As** Arsenic 74.92160 (2 8 18 5)
49 **In** Indium 114.818 (2 8 18 18 3)	50 **Sn** Tin 118.710 (2 8 18 18 4)	51 **Sb** Antimony 121.760 (2 8 18 18 5)

# of valence electrons → determines how substance will bond

- *Elemental semiconductors*
  - Group IV (e.g. - Si, Ge)
  - Silicon is the dominant semiconductor
  - Transistors, photovoltaics (solar cells)

more than 1 element

- Compound semiconductors
  - Combination of Group III and Group V elements (GaAs, InP, GaN)
  - Advanced transistors, LEDs, laser diodes, photovoltaics, photodetectors
  - Can also have combinations of Group II and Group VI materials (HgCdTe)

great for light-emitting apps.

III-V Semiconductor Materials

Group III	Group V
5 B Boron 10.811 (2 3)	7 N Nitrogen 14.0067 (2 5)
13 Al Aluminium 26.9815386 (2 8 3)	15 P Phosphorus 30.973762 (2 8 5)
31 Ga Gallium 69.723 (2 8 18 3)	33 As Arsenic 74.92160 (2 8 18 5)
49 In Indium 114.818 (2 8 18 18 3)	51 Sb Antimony 121.760 (2 8 18 18 5)

- Consist of group III and group V elements (essentially alloys)
- III-Nitrides:
  - Visible lasers and LEDs (Sony Play Station, solid-state lighting)
  - High-power transistors
- III-Phosphides: (InP_3)
  - Infrared lasers (telecommunications)
  - High-speed transistors
  - Photovoltaics
- III-Arsenides: ($GaAs$)
  - Red lasers and LEDs
  - High-speed transistors
- III-Antimonides:
  - Mid-wavelength infrared lasers
  - Thermal cameras (photodetectors)
  - High-speed electronics

Gallium Oxide → Super high voltage switching

Types of Solids

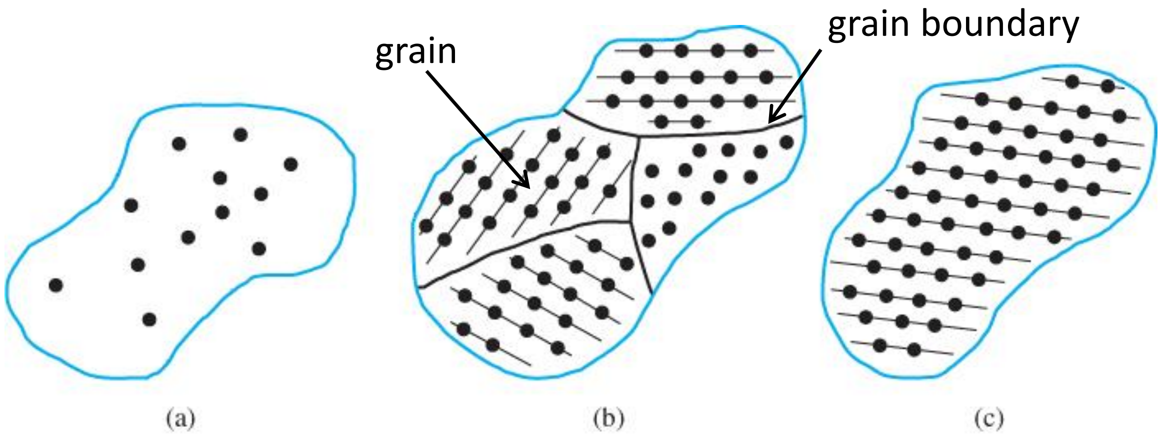


Figure 1.1 | Schematics of three general types of crystals: (a) amorphous, (b) polycrystalline, (c) single.

- Amorphous – order within a few atomic or molecular dimensions
- Polycrystalline – order over many atomic or molecular dimensions. Ordered regions are called *grains*. Interfaces are *grain boundaries*.
  grain boundaries cause electron scattering
- Single Crystal – high degree of order and geometric periodicity. Superior electrical properties. silicon very good

Space Lattices

- In this course, we are interested in single crystal materials
- *Lattice:* periodic arrangement of atoms in the crystal
- *Lattice point*: a particular atom in the lattice
- *Unit cell:* small volume of the crystal that can be used to reproduce the entire crystal by translation
- *Primitive cell:* smallest unit cell that can be repeated to form the lattice

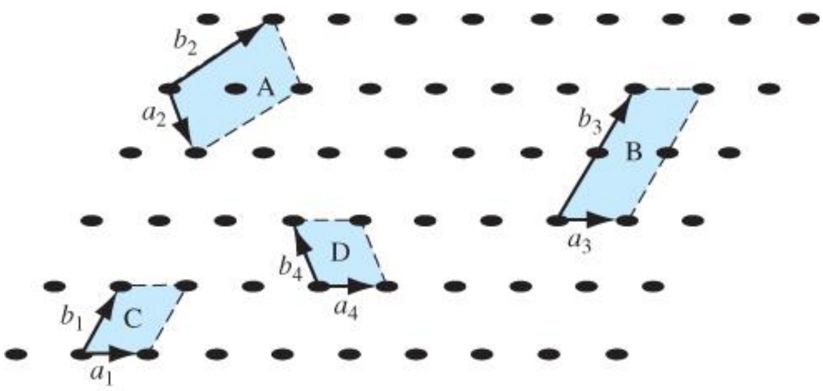


Figure 1.3 | Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

Space Lattices

- A lattice may be generalized to three dimensions
- The lattice is reconstructed by repeating the unit cell
- Every point on the lattice can be represented by

$$\boxed{\bar{r} = p\bar{a} + q\bar{b} + s\bar{c}}$$

$\bar{a}, \bar{b},$ and $\bar{c}$ are basis vectors

p, q, s are integers

$||\bar{a}|| \quad ||\bar{b}|| \quad ||\bar{c}||$

are the *lattice constants*

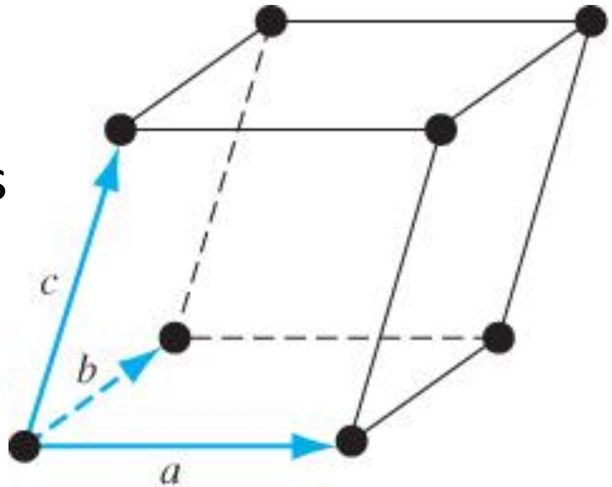


Figure 1.4 | A generalized primitive unit cell.

Common Lattice Types

Simple Cubic (SC) Body-Centered Cubic (BCC) Face-Centered Cubic (FCC)

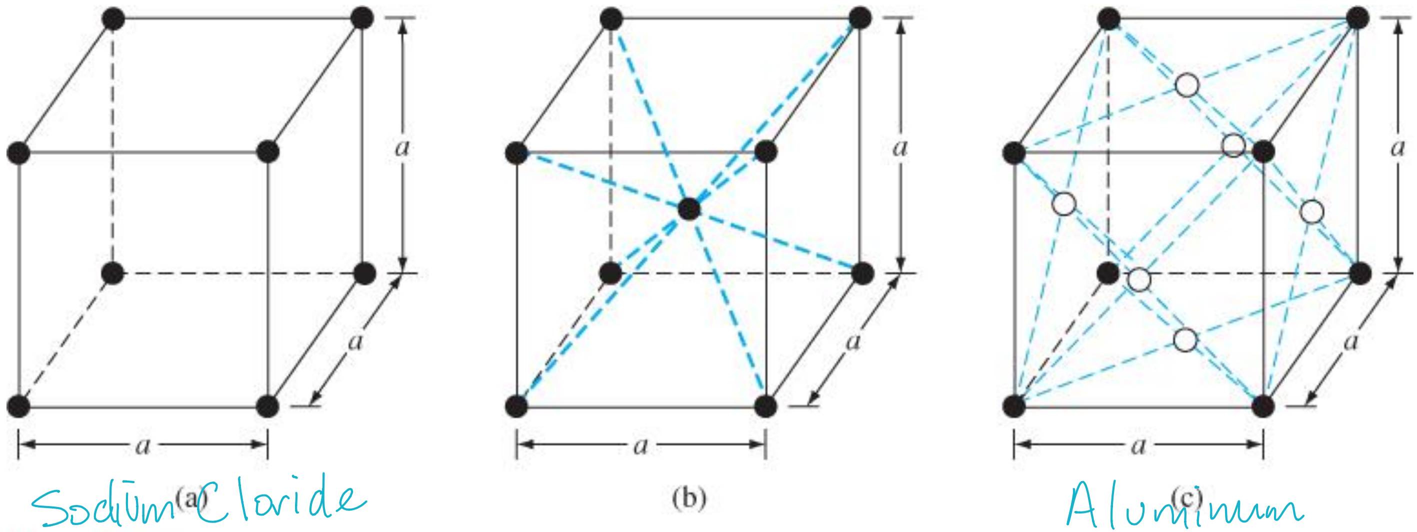
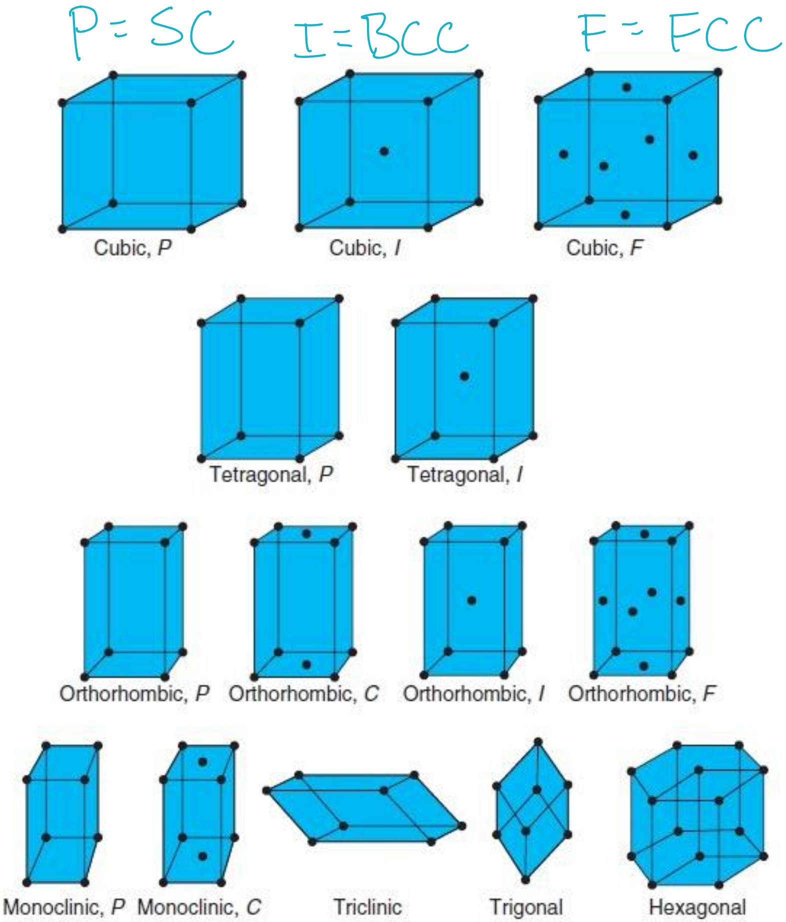


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

- Basis vectors ($\bar{a}, \bar{b}, \bar{c}$) are orthogonal and equal in length (a)
- Knowledge of the crystal structure allows us to determine the volume density of atoms or surface density of atoms on a given plane

Sodium forms in diamond structure (2 FCC)

Bravais Lattices



- In general, there are 14 possible 3D lattice configurations (Bravais lattices)
- All 3D lattices can be constructed from one of these unit cells
- In this class, we will deal primarily with SC, BCC, and FCC
- Sometimes we may discuss hexagonal (GaN, ZnO)

Volume Density of Atoms

Objective: Find the volume density of atoms in a crystal.

EXAMPLE 1.1

Consider a single-crystal material that is a body-centered cubic, as shown in Figure 1.5b, with a lattice constant $a = 5\ \text{Å} = 5 \times 10^{-8}$ cm. A corner atom is shared by eight unit cells that meet at each corner so that each corner atom effectively contributes one-eighth of its volume to each unit cell. The eight corner atoms then contribute an equivalent of one atom to the unit cell. If we add the body-centered atom to the corner atoms, each unit cell contains an equivalent of two atoms.

■ Solution

The number of atoms per unit cell is $\frac{1}{8} \times 8 + 1 = 2$

The volume density of atoms is then found as

$$\text{Volume Density} = \frac{\#\ \textit{atoms per unit cell}}{\textit{volume of unit cell}}$$

So

$$\text{Volume Density} = \frac{2}{a^3} = \frac{2}{(5 \times 10^{-8})^3} = 1.6 \times 10^{22}\ \text{atoms/cm}^3$$

■ EXERCISE PROBLEM

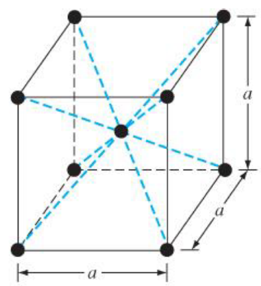
Ex 1.1 The lattice constant of a face-centered cubic lattice is 4.25 Å. Determine the (a) effective number of atoms per unit cell and (b) volume density of atoms.
[Ans. (a) 4; (b) 5.21×10^{22} cm^{-3}]

*see in class notes for discussion

Volume Density of Atoms $\longrightarrow \dfrac{\#\text{ atoms per unit}}{\text{volume unit}}$

Ex 1.1

Body-Centered Cubic (BCC)



$\dfrac{2}{a^3}$

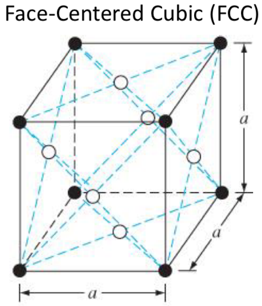
$a = 5\text{Å} = 5\times10^{-8}\,\text{cm}$

(roughly half a nanometer)

$$\frac{2}{(5\times10^{-8})^3} \approx 1.6\times10^{22}\ \frac{\text{atoms}}{\text{cm}^3}$$

Exercise 1.1

Face-Centered Cubic (FCC)



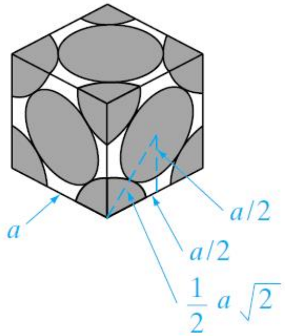
$$\frac{\#\text{ atoms}}{\text{volume}} = \frac{4}{a^3}$$

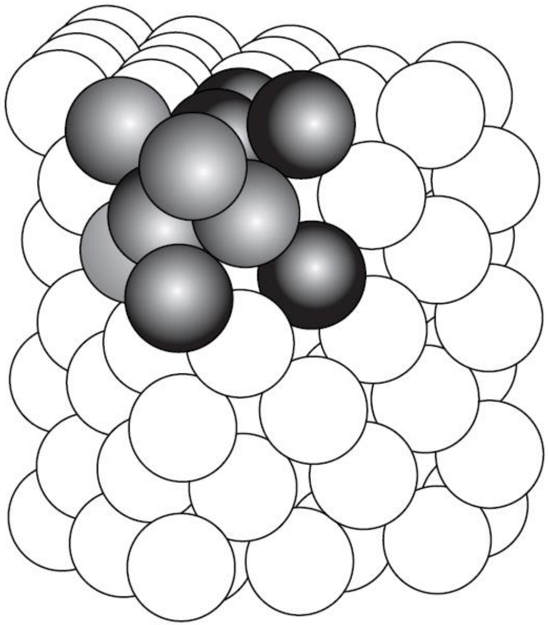
$$= 5.21\times10^{22}\ \frac{\text{atoms}}{\text{unit}}$$

Packing Fraction of Atoms

Figure 1–4
Packing of hard spheres in an fcc lattice.

*from Streetman text





$$packing\ fraction\ (PF) = \frac{volume\ of\ spheres\ in\ unit\ cell}{volume\ of\ unit\ cell}$$

*we assume that atoms are hard spheres and that nearest neighbors touch

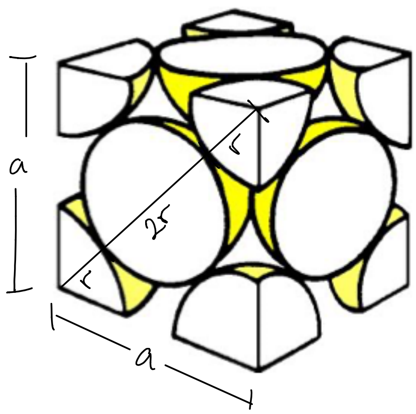
*see in class notes for discussion

Packing Fraction of Atoms:

what volume of the material is occupied

1: what are the nearest neigh.

2: relationship between a & r



$$4r = \sqrt{2}\,a$$

$$r = \frac{\sqrt{2}}{4}a$$

assuming hardpacked sphere $\rightarrow \frac{4}{3}\pi r^3$

$$V_{atom} = \frac{4}{3}\pi\left(\frac{\sqrt{2}}{4}a\right)^3$$

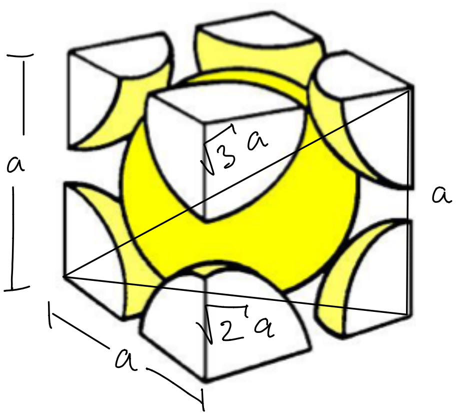
we'll see that a goes away so that all that matters is structure type

$$\text{Total atom volume} = \underset{\uparrow \atop \frac{\text{atoms}}{\text{unit}}}{4} \times \frac{4}{3}\pi\left(\frac{\sqrt{2}}{4}\right)^3 a^3$$

Packing Fraction = $\dfrac{\text{Volume of spheres in unit}}{\text{Volume of unit cell}}$

$$PF = \frac{4 \times \frac{4}{3}\pi\left(\frac{\sqrt{2}}{4}\right)^3 \cancel{a^3}}{\cancel{a^3}} \approx 0.74 = 74\%$$

FCC is highest packing fraction



$4r = \sqrt{3}\,a$

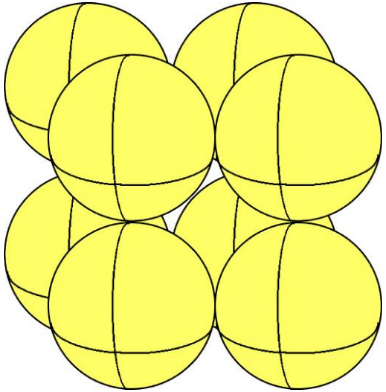
$r = \dfrac{\sqrt{3}}{4}a$

Total atom volume = $\underset{\uparrow \\ \frac{\text{atoms}}{\text{unit}}}{2} \times \frac{4}{3}\pi\left(\frac{\sqrt{3}}{4}\right)^3 a^3$

$$PF = \frac{2 \times \frac{4}{3}\pi\left(\frac{\sqrt{3}}{4}\right)^3 \cancel{a^3}}{\cancel{a^3}} \approx 0.68 = 68\%$$

Packing Fraction of Atoms

Simple Cubic (SC)



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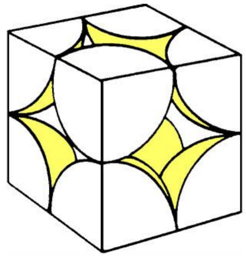
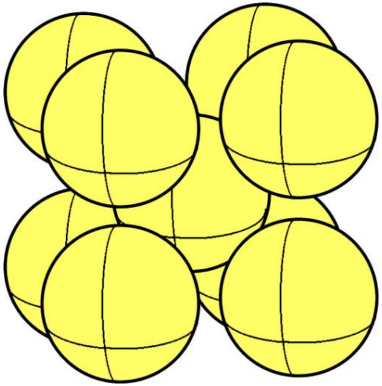


Body-Centered Cubic (BCC)



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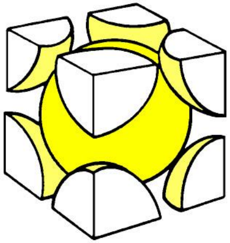
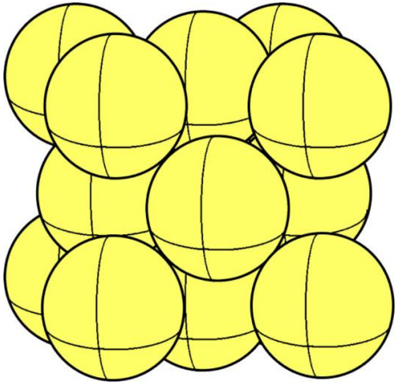


Face-Centered Cubic (FCC)



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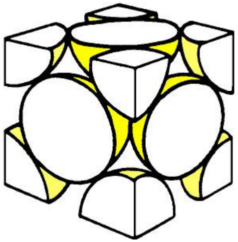

- FCC has the highest packing fraction for cubic lattices (74%)
- FCC is "close packed"
- What are the packing fractions for SC and BCC?